Numerical Investigation of Chemical and Volume Control System Behavior in Normal Operation and Incident Situation

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***Abstract*-The characteristics of the Chemical and Volume Control System (CVCS) in normal operation and accident situation will leave a remarkable impact on the power plant availability and safety. The CVCS and Safety Injection System (SIS) are numerical investigated with the Computational Software, Flowmaster V7.5, and the models are validated with design data. The charging and seal injection maximum flowrates variations with Reactor Coolant System pressure are predicted during the Steam Generator Tube Rupture (SGTR) accident, and different system operations are simulated and compared in detail. The results show that one low head safety injection pump of SIS is necessary and adequate to increase the charging and coolant pump seal injection flow significantly.**

Keywords-Reactor Coolant System (RCS)；Chemical and Volume Control System(CVCS)；Safety injection System(SIS)；Steam Generator Tube Rupture (SGTR)；Numerical Simulation

NOMENCLATURE

ΔP: pressure loss, unit: Pa,

ξ : loss coefficient;

$\dot{m}$: mass flowrate, unit: kg/s;

ρ : density, unit: kg/m^3;

A : section area, unit: m^2;

a_{ij} : coefficient of Matrix

I. INTRODUCTION

With the rapid development of computational fluid dynamics and computer simulation technology, the numerical simulations are more and more popular in nuclear power plant design, operation, and safety analysis [1-3]. The design of nuclear pressurized water power plant requires that auxiliary and safety guard systems will perform their respective functions with adequate system margins, which will ensure the reactor be shut down safely during any accidents to prevent radioactive coolant from being released into the environment. It is quite expensive for experimental test to achieve the system hydro-thermal behavior, and the experimental results would be only applied in some spectacular scenarios, while the computational simulation can easily achieve the system hydraulic-thermal behavior not only in normal operation but also in accidents [2, 3].

The target of this paper is to obtain the maximum or minimum flowrate of the chemical and volume control system in Steam Generator Tube Rupture (SGTR) accident.

A. CVCS and SGTR

Chemical and Volume Control System (CVCS) The chemical and volume control system (CVCS) is designed to provide the services of volume control, chemical control and water injection to reactor coolant pumps (RCP) seals to the Reactor Coolant System (RCS). The CVCS provides makeup for small leaks up to a 3/8 inch diameter process line or tubing or a steam generator tube leak within the Reactor Coolant Pressure Boundary which allows the plant to be taken to cold shutdown conditions without the any actuation of the safety guarded systems. If the break or crack of pipe line continues to grow, the safety-related system will take place with the safety-guarded system, such as the Safety Injection System. In this case, the CVCS charging pumps operate as high head safety injection (HHSI) pumps. The safety injection operation mode automatically overrides all others [4].

The CVCS is composed of the following sub systems: charging and letdown, purification, seal injection, as shown in Figure 1. The reactor coolant with temperature of 292℃ and pressure of 15.5MPa is discharged from cold leg of RCS and then passed through the shell side of a regenerative heat exchanger with tube side filled with 54℃ coolant, after that, reactor coolant is depressurized by one of the three parallelized orifices, and continued to be cooled down by the letdown heat exchanger with shell side fulfilled with component cooling water of 35℃. If the letdown flow temperature is below 57℃, it will be demineralized to remove fission and activation products in ionic form or as particulates from the RCS to ensure that operating activity levels are consistent with the plant technical specifications and industry guidance. Finally the letdown flow is dropped into a tank with the name of volume control tank. The previous process is letdown and purification. Three centrifugal pumps are designed to provide the charging flow and injection water to the RCPs from volume control tank, but only one of them is engaged in normal operation. These processes are charging and seal injection of CVCS, which can maintain the RCS inventory and cool down the bearings of RCPs. In normal operation, the charging pump is responsible for charging flow and coolant pump seal injection. If the safety injection is actuated in accident operation, the charging pump is also employed as high pressure safety injection pump and the pump suction will be switched from the volume control tank to the refueling tank.

B. Accident of Steam Generator Tube Rapture (SGTR)

There were several accidents known as the Steam Generator Tube Rapture taken place in some nuclear power plants. The Steam Generator Tube Rapture is postulated as the design based accident (DBA) during the plant design. It is defined that one or more heat transfer tubes inside steam generator breaks or there is cracks on the tubes, which will lead to slight and continuous leaks inside steam generator. The second safety barrier (primary pressure boundary) will be

broken and the radioactive coolant will be released from the primary side to the secondary side [5].

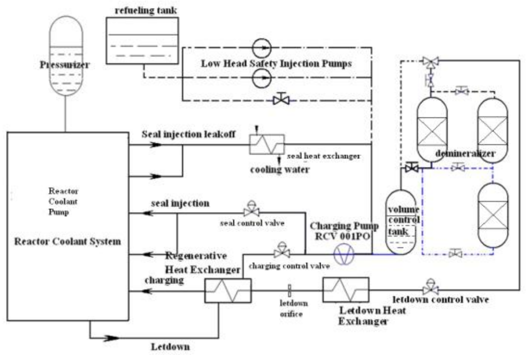


Figure 1 The systematic and simplified diagram of the chemical and volume control system

At the beginning of the leakage from the cracks or breaks on tubes of the steam generator, the pressure of reactor primary side will decrease and the chemical and volume control system will increase the charging flow to maintain the primary inventory, meanwhile the letdown flow will even be isolated according the leakage. As the crack size increases, the leakage will be significantly increased and the charging capability of the chemical and volume control system will not meet the requirement of the primary side. The pressure of primary side will continuously decrease and reach the low pressure setpoint of pressurizer. The reactor is going to be shut down emergently and the turbine is tripped off. The safety injection system will be actuated to recover the pressure and coolant loss of primary side. At the end of safety injection operation, the safety injection mode of the Reactor Safety Injection System will be switched into the charging mode of the Chemical and Volume Control System. The charging pump will be switched over to suck from refueling tank back to the volume control tank; one or more Low Head Safety Injection pumps are chosen to enhance the charging pump inlet pressure.

Charging, letdown and coolant pump seal injection are balanced for each other to maintain the primary inventory. So the relation of these three flows limits and primary coolant pressure in accident situation will determine whether the reactor will be shutdown safely without any actuation of safety guarded system.

C. *Purpose of the Modeling*

The behavior of the chemical and volume control system in accident is the input of the safety analysis or possibility safety analysis (PSA). The following curves are necessary to perform the reactor safety analysis: the relation of minimum letdown flowrates and primary coolant pressure, maximum charging flowrates and coolant pump seal injection variation with primary coolant pressure, if the suction of charging pump is switched from volume control tank to refueling tank. Why the above information is necessary for the safety analysis is out of the scope of this paper and will not be discussed in the following sections.

II. MODELING AND VERFICATION

A. *Modeling Introduction*

The hydraulic simulation software Flowmaster 7.5 is employed to achieve the objects discussed previously in section 2.3. The pressure loss of any individual equipment, valve, pipe is simulated with following definition (1) [6].

$$\Delta P = \frac{1}{2}\frac{\xi \dot{m}^2}{\rho A^2} \tag{1}$$

According to a large pipe network with various equipments, such as Figure1, the pressure, flowrate and temperature of the pipe network should be achieved with the large sparse semi-triangle matrix (equation 2) calculation. In equation 2, a_{ij} is a element of coefficient matrix [7].

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{m1} & \cdots & \cdots & \cdots & a_{mn} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \cdots \\ \cdots \\ P_m \end{bmatrix} = \begin{bmatrix} \dot{m}_1 \\ \cdots \\ \cdots \\ \dot{m}_m \end{bmatrix} \tag{2}$$

B. *Model Parameters*

The open ratio of every control valves of CVCS system in normal operation will be obtained by the design pressure drop of each control valve and the corresponding Cv variation with the open ratio. In normal operation, the open ratio of letdown, charging and seal injection control valves are 0.2971, 0.42, and 0.3676 respectively.

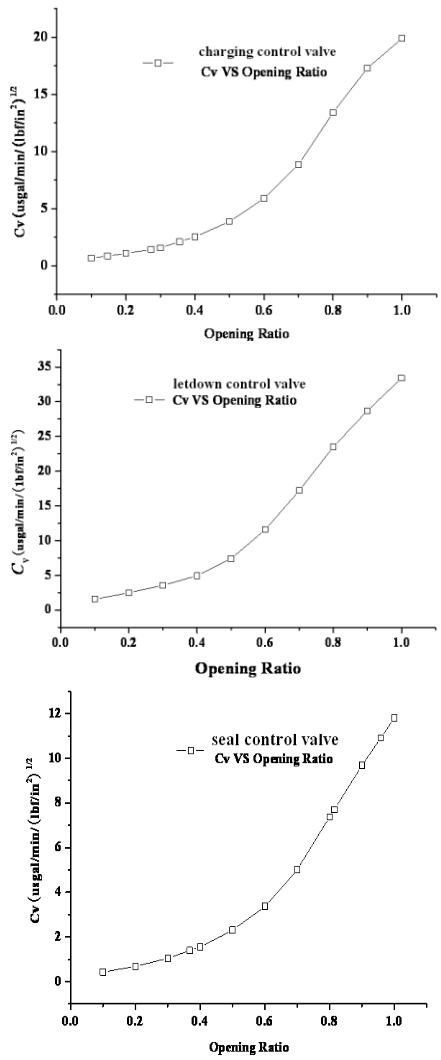


Figure 2 Flow coefficients Cv variation with open ratio of CVCS control valves

C. Coolant Physical Properties

The software Flowmaster only provide the 0~120℃ water physical properties, but the temperature of CVCS coolant is varied from 46~292℃ while pressure is varied from 0.17MPa to 15.5MPa. It is necessary to rebuild the database of coolant thermal physical properties. The coolant density and viscosity variations with temperature and pressure are predicted with the IAPWS Industrial Formulation 1997 for the thermodynamic properties of sater and steam [8,9]

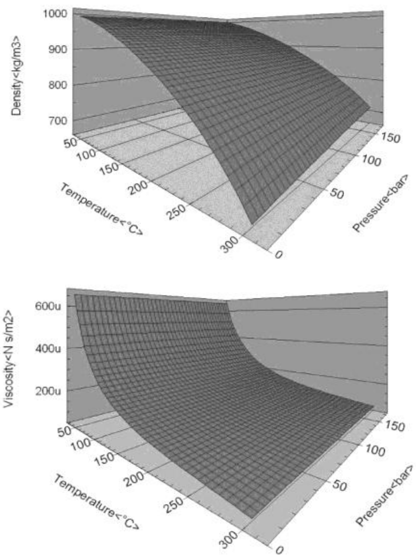


Figure 3 The coolant density and viscosity variation with temperature and pressure[9]

D. Verification of Model

The normal operation of the chemical and volume control system is simulated with the validation with system design data. The result shows that the maximum error between results and design reference value is 6.78%, the minimum is 0.09%. It is reasonable to believe that this model has adequate accuracy to simulation the system behavior in accident situation.

TABLE 1 COMPARISON BETWEEN SIMULATED VALUE AND SYSTEM DESIGN VALUE

Node position	p (bar)	err%	Q (t/h)	err%	T (℃)	err%
inlet of regenerative heat exchanger shell side	158/154.86	2.0	13.44/13.	0.74	292/292.4	0.14
outlet of regenerative heat exchanger shell side	—/154.22	—	—/13.54	—	140/139.8 7	0.09
Inlet of letdown orifice	155/153.78	0.7	13.44/13. 4	0.74	140/139.8 8	0.09
Letdown heat exchanger upstream	26/24.93	4.2	13.44/13. 4	0.74	140/143.1 3	2.19
outlet of charging pump	177/174.84	1.2	29.3/29.1	0.58	54/53.22	1.47
Seal water heat exchanger upstream	2.2/2.29	3.9	15.7/15.5	1.29	54/57.42	5.96
charging control valve upstream	177/174.82	1.2	10.3/10.2	0.39	54/53.23	1.45
charging control valve downstream	158.3/155.3	1.9	10.3/10.2	0.39	54/53.70	0.56
outlet of regenerative heat exchanger tube side	158/155.23	1.7	10.3/10.2	0.39	263/265.7 1	1.02
seal control valve upstream	177/174.81	1.2	5.4/5.37	0.56	54/53.23	1.45
seal control valve downstream	156.1/155.9	0.1	5.4/5.37	0.56	54/53.68	0.60

III. RESULTS AND DISCUSSION

A. Minimum Letdown Flowrates with Different Reactor Coolant Pressure

Minimum letdown operation is defined as the following situation: one letdown orifice is open; the pressure and temperature of reactor coolant system should be chosen to make the letdown flow to be as less as possible; the letdown control valve is fixed in a certain position which will make the letdown flow to be the minimum.

Figure 4 is plant normal operation status diagram, after SGTR accident, curve A or cure B will be chosen to be as the boundary conditions of minimum letdown simulation. So which curve will lead to a less letdown flow can be compares by a single test. The numerical test can be performed to compare the different letdown flows with different coolant letdown temperatures (T_{RCP} = 200 ~ 292.4℃) while the coolant pressure is fixed as a constant, 15.5MPa, for example.

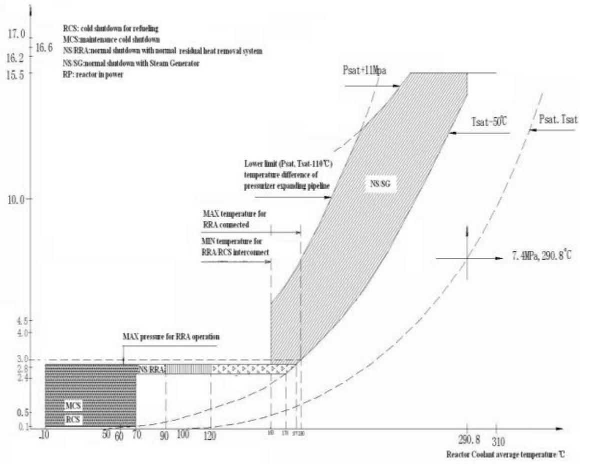


Figure 4 Pressurized water nuclear power plant normal operation diagram

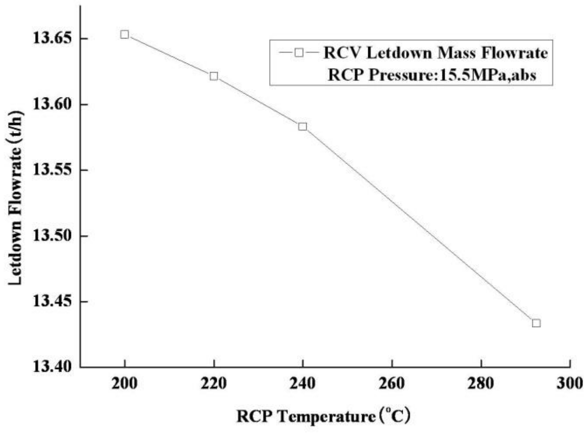


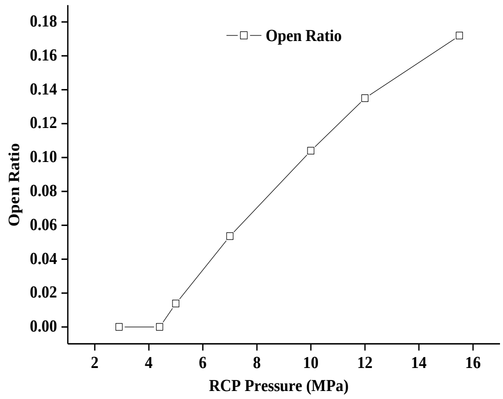
Figure 5 Letdown flowrates with different coolant temperatures at a fixed pressure 15.5Mpa

Figure5 is the comparison results with different coolant temperatures at a fixed pressure 15.5Mpa. It is clear that curve B will result in less letdown flow.

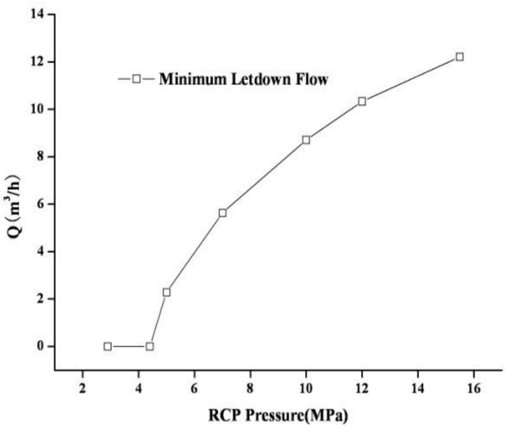
Open ratio of the letdown control valve is also an important parameter in the minimum letdown simulation. One extreme situation is to keep the control valve closed and the letdown flow zero. But this situation is hardly to achieve because of the control valve design pressure of 4.4MPa(a). So

the reasonable minimum letdown will be a certain flowrate which will lead the inlet pressure of the control valve to overpressure. As the coolant pressure is less than 4.4MPa, the letdown control valve will be totally closed and the letdown flow will be zero, as shown in Fig.6.

Open ratio of 0.3 is the normal position of CVCS letdown control valve, The Figure8 shows that letdown flowrate is sensible when letdown control valve open ratio is less than 60%, while the letdown flowrate seems to be independent with the valve open ratio when it is more than 60%.



a. control valve open ratio variation



b. minimum letdown flowrates variation

Figure 6 Control valve open ratio and minimum letdown flowrates variation with different reactor coolant pressure

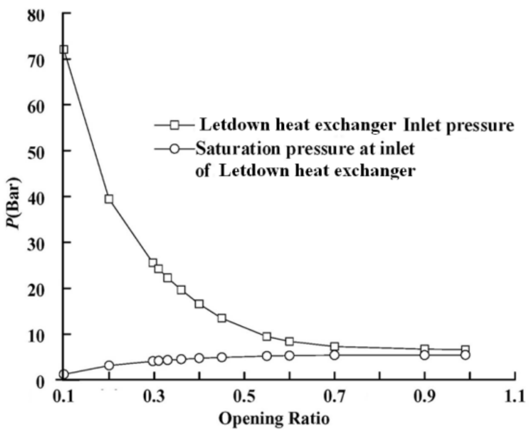


Figure 7 CVCS letdown heat exchanger inlet pressure and saturation pressure variation with letdown control valve open ratio

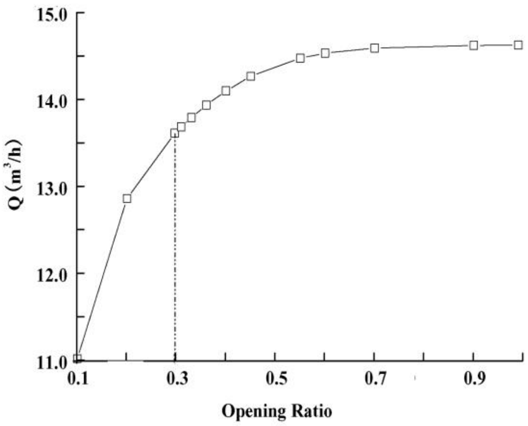
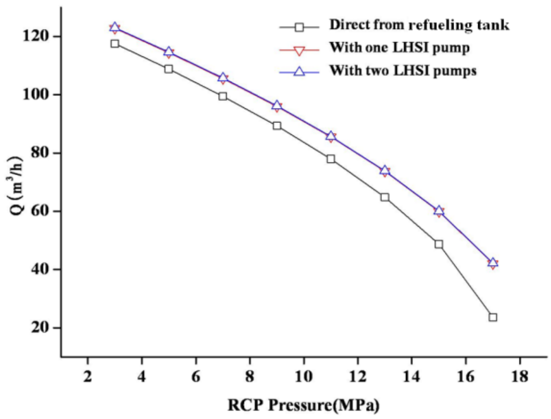


Figure 8 Letdown flowrate with different open ratio of letdown control valve

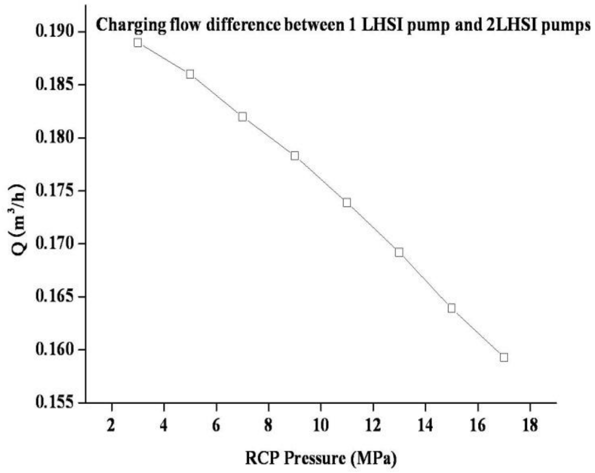


a.Maximum charging flow in three modes

In order to obtain the influence of letdown control valve open ration to letdown flowrate, we adjusted the open position of CVCS letdown control valve in normal power plant operation. The letdown control valve is designed to control the letdown flow pressure to prevent letdown coolant from flashing. During the open ratio increases, the vaporization will not allowed in the letdown process. Figure7 shows that the saturation pressure and actual pressure of letdown process vary with the different open ratio of letdown control valve. The inlet of letdown heat exchanger is chosen to monitor the flashing process because this node is the most possible point with high temperature and low pressure to vaporize the coolant. In normal operation, even if the letdown control valve is fully open, the coolant will not vaporize in the letdown pipes. As the control valve open ratio increases, coolant pressure in the letdown pipes will increase more closely to the coolant saturation pressure with the corresponding letdown temperature.

The Maximum Charging and Coolant Pump Seal Injection Flow with Different Reactor Coolant Pressure This simulation is to compare the different charging modes in SGTR situation. One mode is that the charging pump is sucked from refueling tank directly to provide charging flow and seal injection, the second mode is that one of the Low Head Safety Injection (LHSI) pumps sucks from refueling tank to enhance the inlet pressure of charging pump, the third mode is that both of the LHSI pumps are employed to enhance the inlet pressure of charging pump (Figure 1). The maximum flows are defined

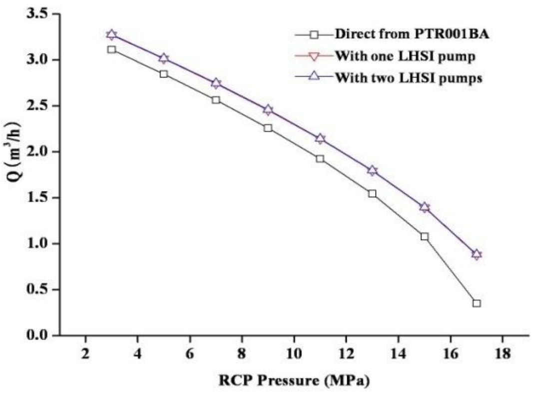
that the control valve on charging line and seal injection line in Figure 1 will be in the full open position.



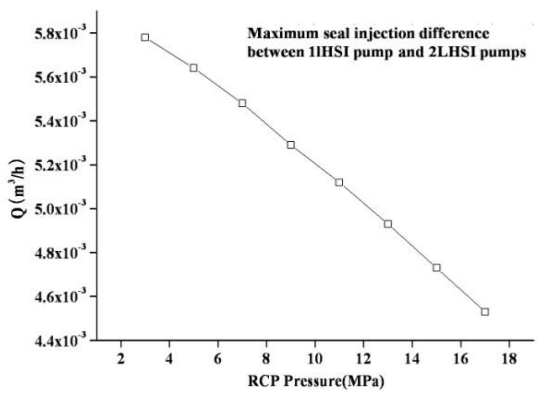
b.Difference between last two modes

Figure 9 Maximum charging flow variation with different pressure of reactor coolant system

The simulation results show that LHSI pump would enhance the maximum charging flow and seal injection flows, Figure 9a and Figure 10a. Two LHSI pumps will not increase these two flows significantly, Figure9b and Figure10b.



a.Maximum seal injection in three modes



b.Difference between last two modes

Figure 10 Maximum seal injection variation with different pressure of reactor coolant system

The result implies that if SGTR takes place, one Low Head Safe Injection pump will be adequate to increase the charging flow and seal injection flow compared to no LHSI pump and two LHSI pumps situations.

B. Discussion of CVCS Simulation

During the modeling of the chemical and volume control system, it is a tough work to establish a hydraulic model by checking thousand pages of pipe construction drawings. If the loss coefficients of the control valves and main high-resistance equipments are dominant, it would be not necessary to review every pipe construction drawing; model building would be turned into high efficiency.

In order to obtain a certain answer, individual equipment, control valves, bends and pipes loss coefficients are compared in normal operation and accident situation. Figure 11 shows that in normal operation, the loss coefficients of control valves and de-pressure orifices, are dominant compared to the pipe, bends and general valves, such gate valves, globe vales and check valves. It also implies that if the simulation of normal operation is required, there is no need to review every pipe construction drawings. But this conclusion is totally different in accident situation, if the maximum charging, letdown and seal injection are required to simulated, the corresponding control valves are fully open, the loss coefficients of the control valves are nearly close to the pipes and bends, which means coordinating of every pipe construction drawing is necessary even this work is pretty time-consuming.

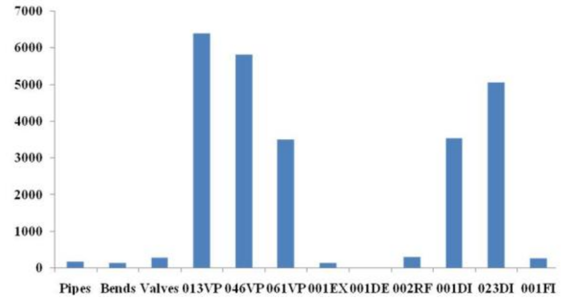


Figure 11 Loss coefficients of individual unit in normal operation

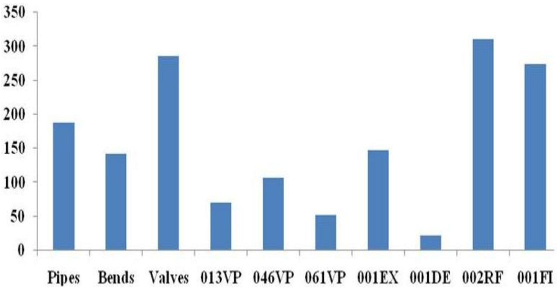


Figure 12 Loss coefficients of individual unit in accident situation

IV. CONCLUSIONS

The hydraulic model of the chemical and volume control system is established to achieve the system behavior in SGTR accident. The following conclusions are summarized during the model simulation.

The theoretic minimum letdown flow will decrease with the reactor coolant depressurization. If the primary pressure is less than 4.4MPa, the theoretic minimum letdown flow will be zero.

Letdown flowrate is sensible when letdown control valve

open ratio is less than 60%, while the letdown flowrate seems to be independent with the valve open ratio which it is more than 60%.

In normal operation, even if the letdown control valve is fully open, vaporizing will not occur in letdown pipes. As the control valve open ratio increases, coolant pressure in the letdown pipes will increase more closely to the coolant saturation pressure with the corresponding letdown temperature.

LHSI pump would enhance the maximum charging flow and seal injection flows, if SGTR takes place, one Low Head Safe Injection pump will be adequate to increase the charging flow and seal injection flow compared to no LHSI pump and two LHSI pumps situations.

In normal operation, the loss coefficients of control valves, and de-pressure orifices, are dominant compared to the pipe, bends and general valves, such gate valves, globe vales and check valves, while in some accident situation, some control valves are fully open, the loss coefficients of the control valves are nearly close to the pipes and bends.

If the simulation of normal operation is required, there is no need to review every pipe construction drawings, but if the system behavior in accident situation is required to simulate, the coordinating of every pipe construction drawing is necessary even this work is pretty time-consuming.

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